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PHOTOCURRENT SUPPRESSION AND INTERFACE STATE RECOMBINATION IN M--ETC(U)
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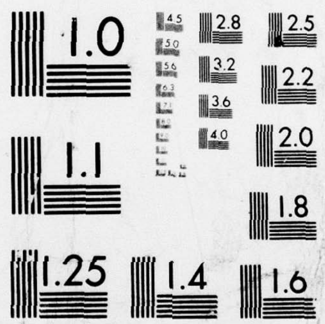

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6 PHOTOCURRENT SUPPRESSION AND INTERFACE STATE RECOMBINATION IN MIS-SCHOTTKY BARRIERS

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ABSTRACT

The purpose of this work is to understand an important degradation mechanism in Schottky barrier photodetectors and solar cells. The I-V characteristcs of Au-nSi devices under illumination show a pronounced photocurrent suppression at low voltages in the presence of an interfacial oxide layer of thickness >or= ≥ 20 A (intentionally introduced) but no suppression in the case of a carefully prepared near-intimate contact. The analysis of these devices takes into account the exchange of charge carriers between interface states and the metal (by tunneling) and between these states and the conduction and valence bands in the semiconductor. As suggested by the experiments, this shows that recombination in the interface states can be important only in the presence of a significant interfacial layer.

INTRODUCTION

The transport properties of MIS-Schottky barriers have received considerable attention in recent years (see, for example refs. 1-3). Less effort has been directed towards the effects of optical illumination on these properties (4,5) and in this paper we consider one aspect of this transport: the collection of photogenerated carriers and the recombination of these carriers in interface states. This description is found to account in a qualitative manner for the mechanism of photocurrent suppression in MIS-Schottky barrier quantum detectors and solar cells. We distinguish between these applications by pointing out that unlike solar cells, quantum detectors are operated in reverse bias and at generally much lower illumination intensities.

EXPERIMENTAL MEASUREMENTS

Au Schottky barriers of area 0.03 cm^2 were fabricated on n-type silicon epi-layers of resistivity 7 Ω-cm by evaporation at a pressure of 10^{-6} torr. Oxidation in dry oxygen was carried out at 720°C and the oxide thickness, d, ranged from 20 A to 50 A. Schematic structure of the MIS-Schottky diode and its energy band diagram are shown in Fig.1. The I-V characteristics in reverse bias (metal negative) for a near-ideal diode with no intentional oxide are shown in Fig.2 as a function of illumination intensity (white light), which shows that the short-circuit photocurrent is not suppressed by the (unavoidable) ~ 10 A oxide grown before evaporation. On the other hand, for an MIS diode with d ~ 35 A (Fig.3), photocurrent suppression is pronounced for small reverse voltages. We note that for sufficient reverse bias V_R the photocurrent suppression effects are removed, such that for the same illumination level, the collected photocurrent J_{ph} is the same for all our oxide thicknesses and equal to that of the near-ideal diode of Fig.2. The magnitude of the threshold voltage V_R increases with illumination intensity, and is also observed to increase with oxide thickness. Moreover the value of the short-circuit current density J_{SC} decreases with oxide thickness. The ratio J_{SC}/J_{ph} is a measure of the photocurrent suppression, and the experimental data is shown in Fig.4 for different oxide thicknesses.

DISCUSSION

As noted previously (3), for MIS-Schottky barriers with ultra-thin oxide layers (≲ 20 A), interface states located at the silicon/oxide interface are in equilibrium with the metal. This means that for MIS-Schottky barrier photodetectors, when the interface states capture an optically generated hole, they release this hole to the metal before an electron can be captured from the conduction band to complete the recombination process. Interface states do not in this case constitute a recombination current and instead, this process contributes to the collected photocurrent.

The short-circuit energy band diagram for an MIS-Schottky barrier under illumination is shown in Fig.5(a). Photogenerated holes are supplied to the semiconductor surface by drift-diffusion processes represented by

$$J_p = p\,\mu_p \frac{dE_{fp}}{dx} \tag{1}$$

For a sufficiently thin oxide (d ≲ 20 A) these holes are readily removed by tunneling into the metal. Under these conditions the photocurrent collected obtains its maximum value, determined by the illumination level.

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As the oxide thickness increases, the tunneling probability is diminished by the factor $\exp(-\chi^{\frac{1}{2}}d)$ where χ is the average potential barrier of the oxide for holes tunneling into the metal. For $d \gtrsim 20$ A (in the Au-SiO_2-nSi system) we have observed that the oxide begins to limit the collected photocurrent. The concentration of holes at the silicon surface increases and this reduces the net current supplied from the neutral region by increasing the diffusion of holes in the opposite direction. The quasi-Fermi level for holes becomes relatively flat in the depletion region ($d E_{fp}/dx$ is small in (1)) and moves closer to E_V at the surface.

At the same time the tunnel current of holes into the metal, given by (3)

$$J_t = \frac{4\pi m_{th} q(KT)^2}{h^3 N_V} p(o)\exp(-\chi^{\frac{1}{2}}d) \qquad (2)$$

increases due to the increase in p(o), the hole concentration at the surface. A balance is struck for which, in the absence of significant recombination in interface states, $J_p = J_t$ and this occurs for a smaller current than was observed for thinner oxides, where the current was not tunnel-limited. We see therefore that suppression of the photocurrent collected at zero bias occurs for $d \gtrsim 20$ A even in the absence of interface states.

Let us now consider further the case of $d \gtrsim 20$ A and include the effects of interface state recombination. Under normal operating conditions, the hole concentration p(o) at the surface is much greater than the electron concentration n(o). This means that recombination in interface states (capture by these states of an hole followed by capture of an electron) is limited by the capture rate of electrons, which for states below the electron Fermi level E_{fn}, is described by (6)

$$J_{rec} = qN\sigma v[(1-f)n(o)] \qquad (3)$$

where N, σ are the density and electron capture cross-section of interface states, v is the thermal velocity of electrons, f is the occupancy function of interface states and n(o) is the surface concentration of electrons. For typical values $N \sim 10^{12}$ states cm^{-2}, $\sigma \sim 10^{-15}$ cm^2 and $n(o) \sim 10^5$ cm^{-3} (determined by a Schottky barrier height ϕ_{bn} of 0.6 eV for the Au-nSi device), $J_{rec} \sim 10^{-10}$ A cm^{-2}. This may greatly underestimate J_{rec} for oxides with positive charges in which case ϕ_{bn} will be reduced from 0.8 eV and n(o) will increase considerably. Large values of σ have also been observed for interface states in these devices (7) under certain conditions (choice of metal, oxide thickness and sample annealing). Provided $J_{rec} \ll J_{SC}$, interface state recombination does not further suppress the photocurrent beyond that suppression due to the oxide layer alone. At low illumination levels, and for lower Schottky barrier height ϕ_{bn}, interface recombination will have a major effect on photocurrent suppression for oxides $\gtrsim 20$ A.

If the MIS-Schottky barrier photodetector is placed under a substantial reverse bias, part of the voltage will be developed across the oxide and this in turn reduces the effective barrier χ. A larger tunneling probability will allow an increased J_t and the hole concentration at the silicon surface will be depleted. This increases the net hole drift-diffusion current, J_p, towards the surface and E_{fp} rises towards the metal Fermi level (Fig.5(b)). For sufficient reverse bias, the short-circuit current is again limited by the photogeneration rate, as in the oxide-free case. It is also clear qualitatively that for an MIS diode, the threshold reverse bias (V_R) for elimination of suppression increases with intensity since more tunnel current must be passed and for a fixed intensity, V_R should increase with the oxide thickness. This is in accordance with experimental data shown in Fig.6 for 3 different oxide thicknesses.

Further investigation is under way regarding the dependence of photocurrent suppression on oxide thickness and interface state parameters. We believe that the threshold V_R for the complete collection of photocurrent and the shape of the photocurrent-voltage curves will help to a basic understanding of interface state processes.

ACKNOWLEDGMENT

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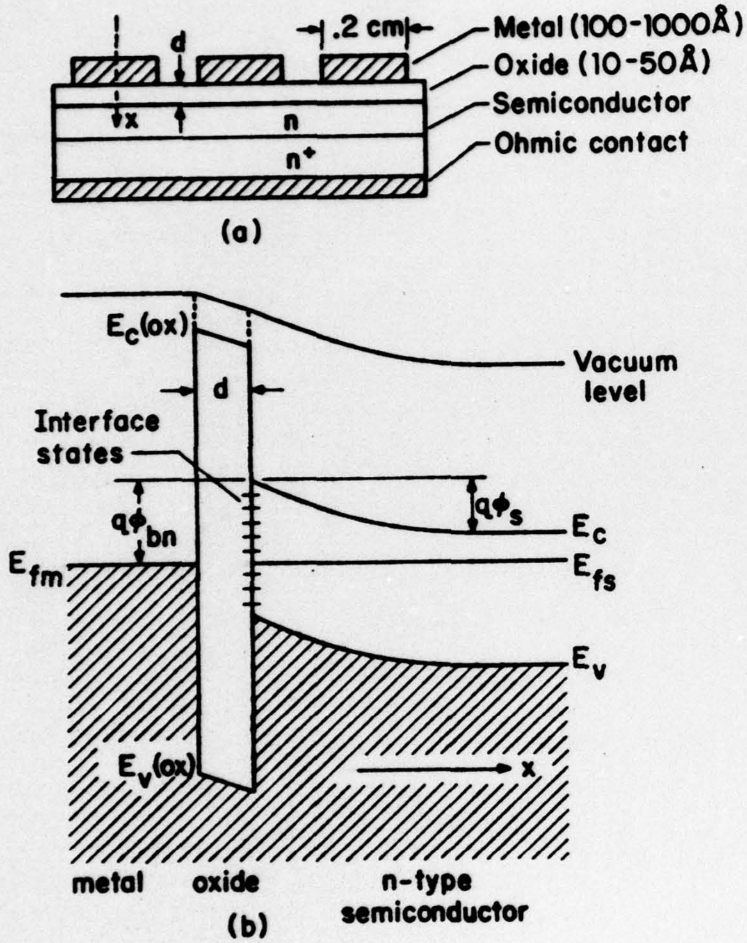

Fig.1. Schematic structure of the MIS-Schottky barrier (a) and the energy band diagram under thermal equilibrium (b).

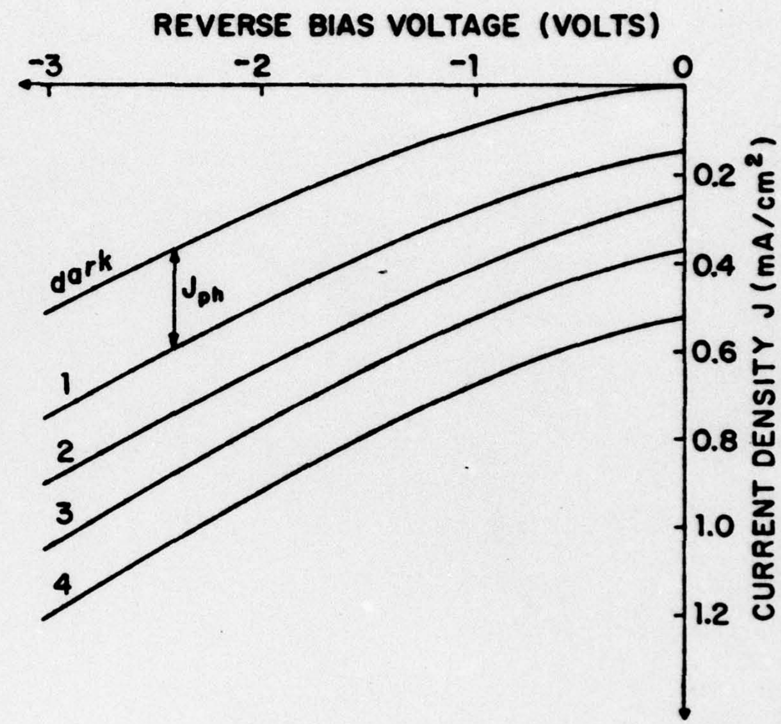

Fig.2. Reverse I-V characteristics of a near-ideal Schottky barrier. 1-4 represent progressively increasing illumination levels.

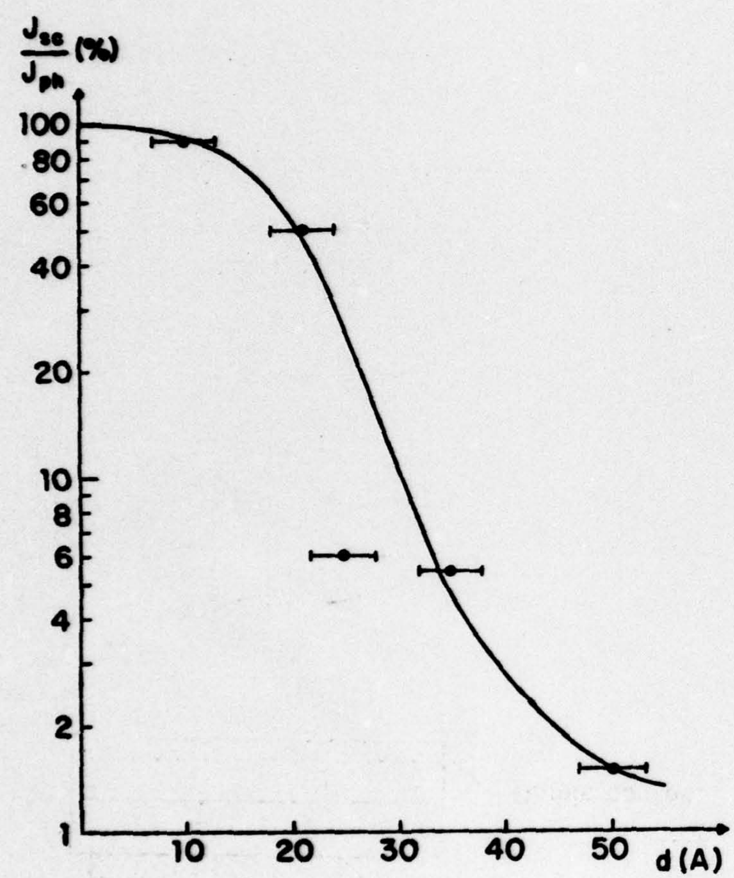

Fig.4. Percentage of photocurrent collected as short-circuit current vs MIS oxide thickness under the same illumination intensity.

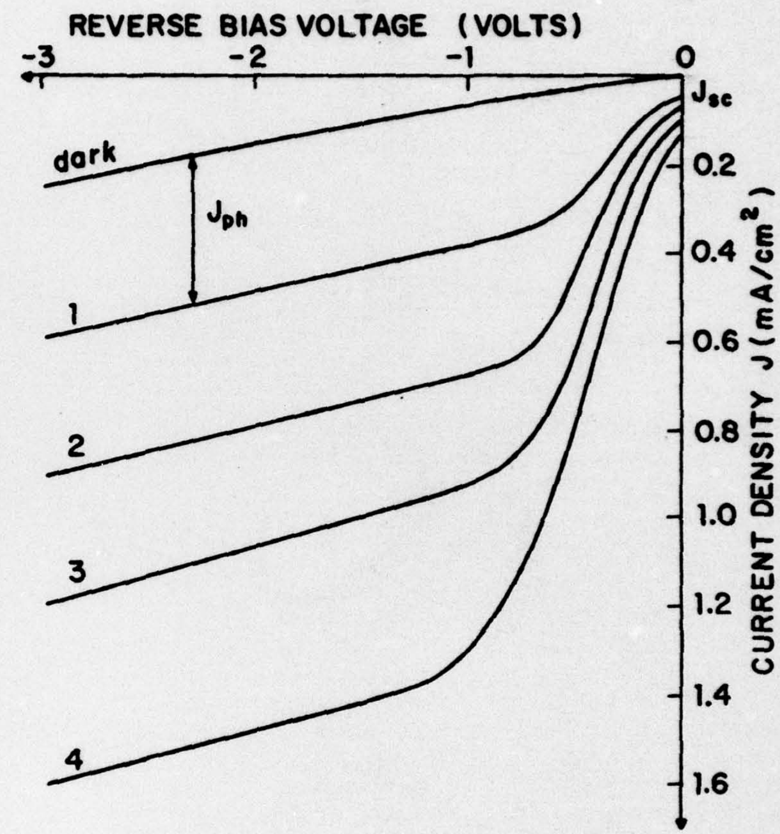

Fig.3. Reverse I-V characteristics of an MIS-Schottky barrier (d ~ 35 A). 1-4 represent progressively increasing illumination levels; these are not the same as in Fig.2.

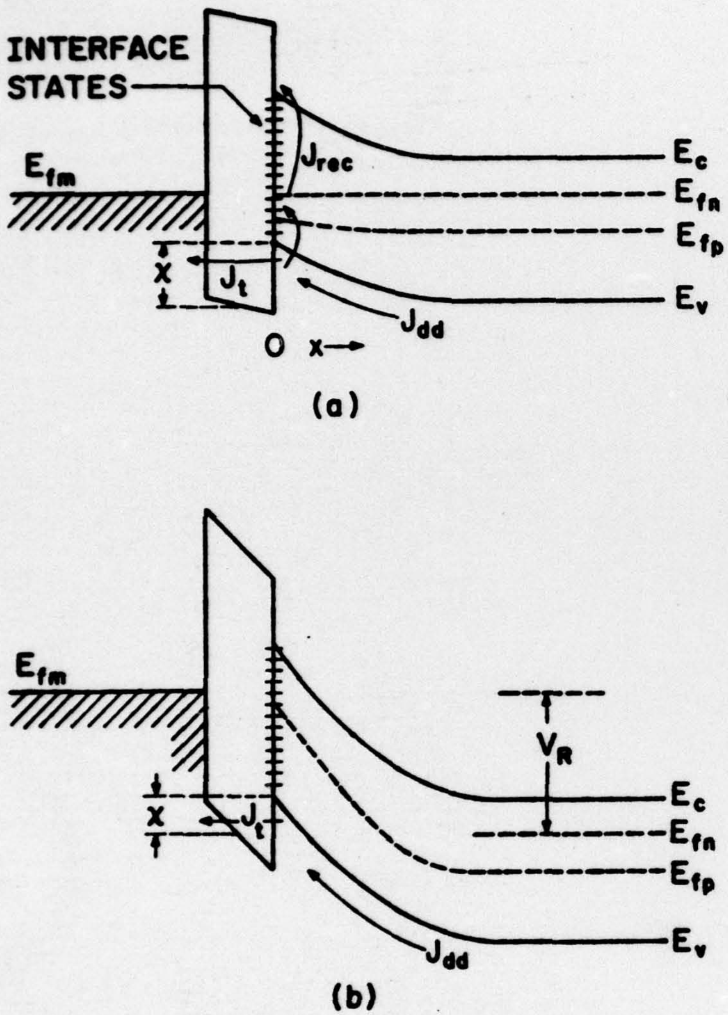

Fig.5. Energy band diagram of an MIS-Schottky barrier under illumination in short-circuit condition (a) and under reverse bias until suppression is eliminated (b).

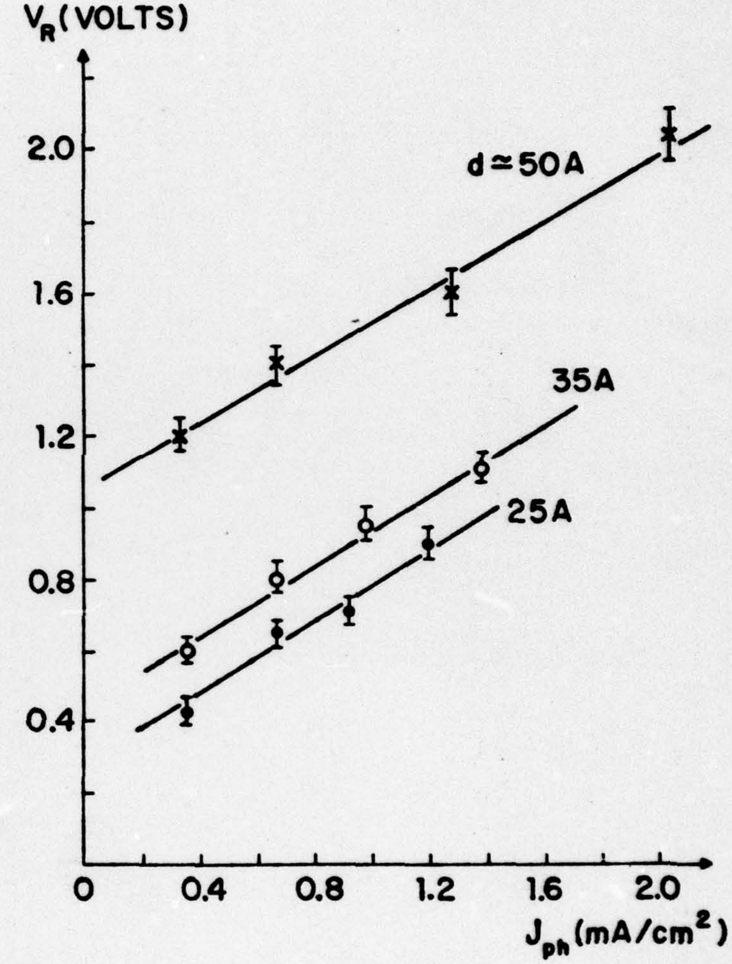

Fig.6. Threshold reverse bias for no suppression vs photocurrent density for 3 different MIS oxide thicknesses.